

Lasers in ophthalmology and the military

Part I: The effects of laser energy on human tissue

Colonel John L Crompton, RAAMC

LASER ENERGY HAS THREE different potential physico-chemical effects on the eye: photocoagulation, photodisruption and photoablation. Each effect has different ocular surgical applications.

In this, the first of two articles, I will outline how laser energy can affect human tissue and how the particular anatomy and optics of the eye allow us to use laser energy to treat various ocular diseases.

A laser (the name is an acronym, from “light amplification

Synopsis

- ◆ The focusing system of the eye (principally the cornea but also the lens) brings laser beams to a sharp focus inside the eye. This carries a risk of injury, but also has therapeutic uses.
- ◆ Laser photocoagulation uses the thermal energy of a laser to seal leaking blood vessels in the eye in diabetic and other vascular disease.
- ◆ Laser photodisruption uses the mechanical energy of a laser to cut through intraocular structures with minimal thermal damage.
- ◆ Laser photoablation is another technique that involves minimal thermal damage. It is used in laser keratectomy to vaporise corneal tissue, reshaping the cornea to correct vision.
- ◆ The typical eye injury from lasers arises from inadvertently looking at a laser source and results in focal damage to eyesight when the retina is burned by the focused laser beam.

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For a basic, non-medical guide to solid-state lasers, see Goldwasser SM. Solid state lasers. In: Sam's Laser FAQ <<http://www.repairfaq.org/sam/laserssl.htm#sslto>>.

by stimulated emission of radiation”) is a highly focused beam of light, which may or may not be in the visible spectrum (Box 1).

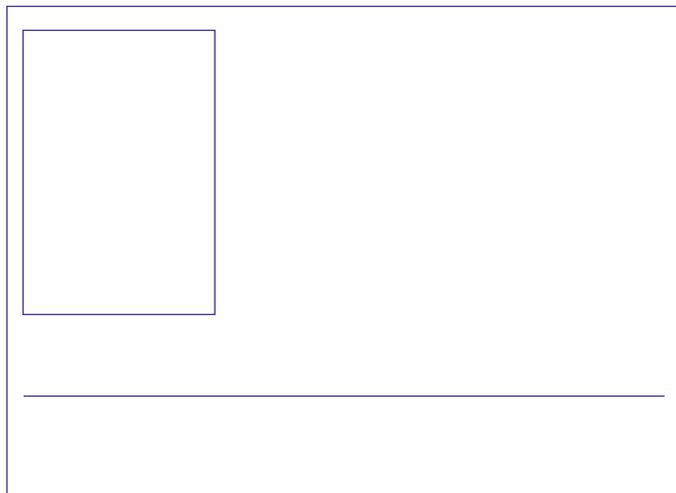
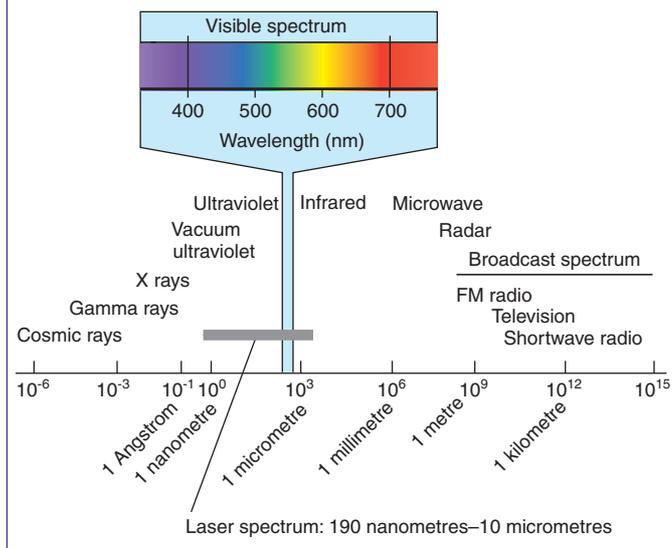
Photocoagulation

Retinal photocoagulation, in which a laser is used to close blood vessels in the retina, was the first medical laser application. Vessels are closed by two thermal mechanisms: intravascular thrombus formation after coagulation of the inner vessel wall,¹ and contracture secondary to thermally induced shrinkage of collagen fibres in the vessel wall.²

Retinal photocoagulation is achieved by laser irradiance of a few hundred watts/cm² with an exposure of less than one second.

Photocoagulation is used in ophthalmology to seal leaking blood vessels in diabetic and other vascular retinal disease, and in other fields of medicine, such as eradicating bladder tumours.

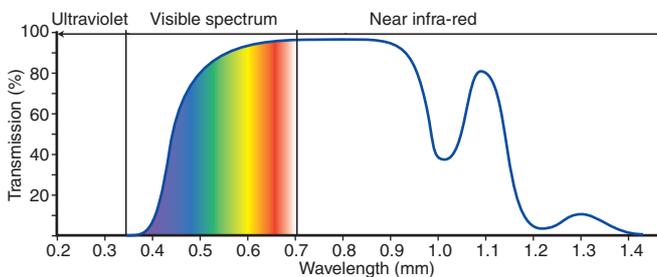
I The radiant energy/electromagnetic spectrum



Photodisruption

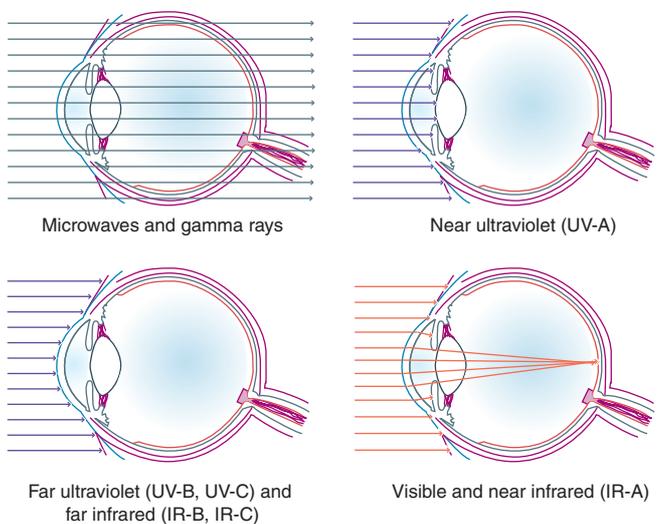
Laser irradiations of up to 1 watt/cm^2 separate tissues by evaporating tissue water or by thermally or photochemically destroying the structure of hard tissue.³ Short laser pulses (eg, $1 \mu\text{s}$) create microexplosions, expanded plasma formation, acoustic waves and cavitations, thus producing mechanical effects with minimal thermal side effects. Q-switched and mode-locked Nd:YAG (neodymium-doped yttrium–aluminium–garnet) lasers are used to disrupt intraocular structures (eg, peripheral iridectomy) and to perform lens capsulotomies.⁴ In urological surgery, photodisruption techniques are used to shatter urinary calculi.

3 The transmission of radiant energy through the human eye

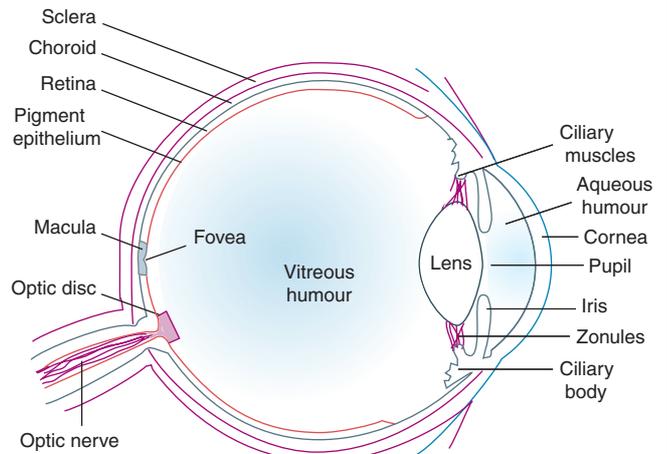


The wavelength of radiant energy determines its transmissibility. Very short wavelength radiation, such as gamma rays, passes through the eye and all human tissues. Wavelengths longer than the visible spectrum are absorbed by skin or the surface of the eye, except for the near infrared wavelengths. Like visible light, these are focused by the cornea and lens and absorbed by the macula.

Diagram (below) modified from Frankhauser F. The danger of laser radiation to the eye. In: Blinding weapons: reports of meetings of experts convened by the ICRC on battlefield laser weapons, 1989–1991: 3-29.



2 The human eye



Photoablation

Photoablation occurs when higher photon energy in short pulses from an excimer laser breaks molecular bonds without causing thermal damage. The vaporised ablated tissue is sucked away. This process is used for corneal surgery. As corneal tissues transmit wavelengths between 400 and 1400 nm, lasers emitting radiation outside this range are needed for corneal surgery. Lasers emitting light in the far-ultraviolet or the far-infrared spectrum are usable, but the argon–fluoride excimer laser, with a wavelength of 193 nm, is the device most often used for photoablation of corneal tissue.

While argon–fluoride lasers can be used to remove corneal scar tissue, they are best known for their ability to sculpt the surface of the cornea. This surface remodelling changes the focusing status of the cornea. The process is known as photorefractive keratectomy (PRK), of which there are two main types: surface PRK and laser-assisted interstitial keratomileusis (LASIK).

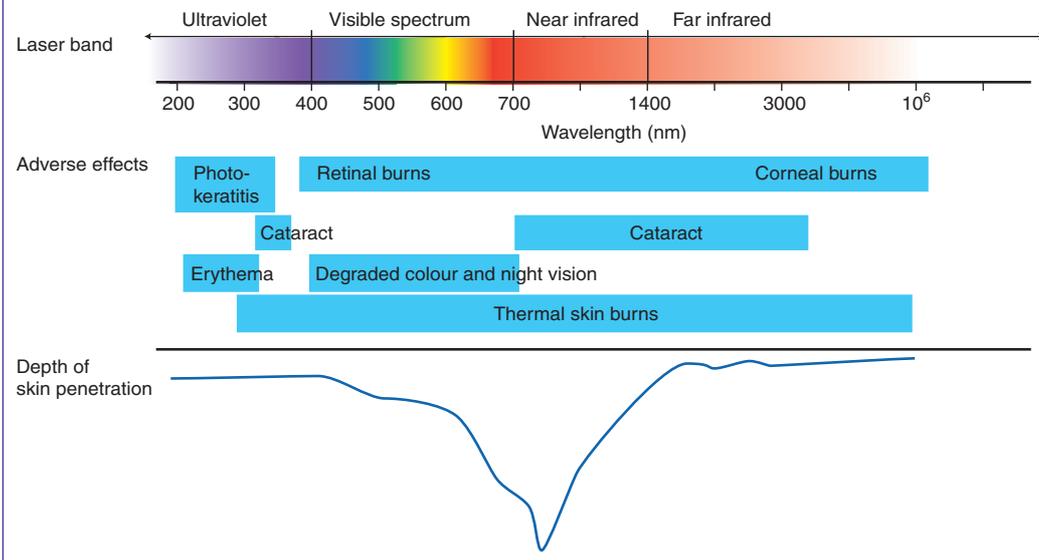
In surface PRK, the corneal epithelium (skin) is first scraped off, and then a computer-driven laser shines through a type of iris diaphragm to project a specific surface contour pattern onto the corneal stroma. In this way, inherent refractive errors, especially myopia (shortsightedness), can be corrected.

In LASIK, the eyeball is stabilised with a suction ring and then a power-driven keratome is used to slice off a cap of corneal epithelium and stroma, which is hinged at one end. Excimer laser is applied to the bed of the cornea and the corneal flap is replaced.

Surface PRK is generally used for correcting lower degrees of myopia (–1.0 to –3.0 dioptres), while LASIK is used for higher corrections (–3.0 to –12.0 dioptres). Greater laser energy is required for higher degrees of myopia than this and can lead to unacceptable corneal haze, scarring and visual degradation. PRK is less effective in the correction of

4 Adverse effects of lasers

Adapted from Sloney DH, Wolbarsht ML. Safety with laser and other optical sources. A comprehensive handbook. New York: Plenum Press, 1980.



all the UV-A. However, the eye is adapted to enable incident radiation between 400 and 1400 nm to penetrate deeply and be focused on the light-sensitive neural retina layer. This waveband includes the visible spectrum (400–780 nm) and the invisible near infrared or IR-A (780–1400 nm).

Box 4 shows that not only the eye but also the skin can be injured by lasers, with infrared lasers having far more penetrance of skin than other wavelengths. This spectral region is known as the “retinal hazard region”, made more so by the increase of irradiance (up to half a million times) between the surface of the cornea and the retina. It is the

longsightedness (hypermetropia) and astigmatic errors (irregular surfaces of the cornea).

Advancing laser technology and computing software is leading to rapid changes in this branch of medicine. As with any form of surgery, complications can occur with both surface PRK and LASIK and result in poor visual outcomes. (The subject of PRK and the military is discussed in detail in “Refractive surgery”, Australian Defence Health Policy Directive No. 201, 16 December 1998.)

Laser diagnostics

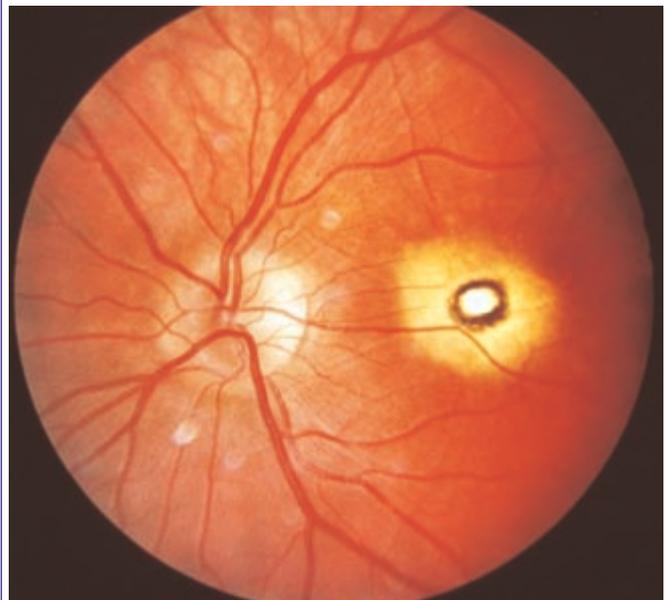
A focused low-level laser beam can be used to scan the fundus of the eye, with the reflected light being decoded in the same manner as in television systems.⁵ This provides an image of the retina and one can measure the depth of the optic cup and the thickness of the retinal nerve fibre layer. Using this system, fluorescein angiography can be recorded digitally. The combination of relatively low light stress, fast frame rate and high resolution has made the scanning laser ophthalmoscope the successor of the ordinary flash lamp fundus camera.⁶

Laser damage to eyes

Light radiation falling on the eye is absorbed by the various outer layers (cornea and sclera) and media (aqueous, lens and vitreous) of the eye, each component behaving as a spectral filter and absorbing specific wavelengths within the incident spectrum (Box 3).⁷ The spectrum of electromagnetic radiant energy is shown in Box 1. All the incident radiation at very short wavelengths in the ultraviolet (UV-B and UV-C) and long wavelengths in the infrared (IR-B and IR-C) ranges is absorbed in the cornea and sclera. The lens absorbs virtually

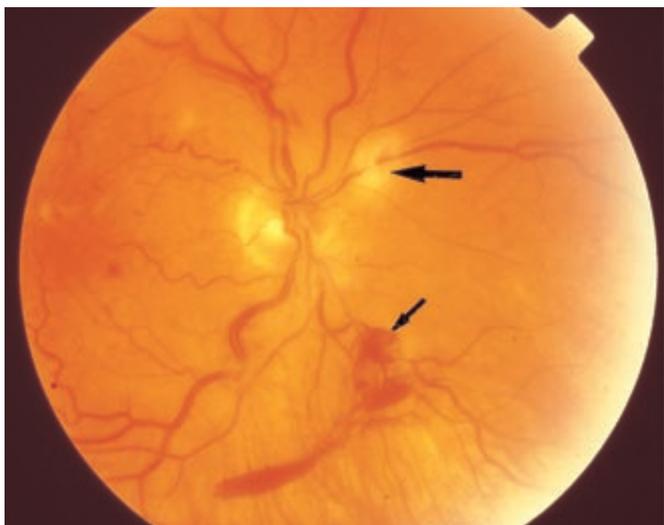
combined refractive power of the cornea and lens that converts the pleasantly warming sensation of sunlight upon the skin to the potentially harmful overexposure of the retina when the eye gazes at the sun (Box 5). Lasers are much more powerful light sources than the sunlight that reaches us through space.

5 Sun burn of the eye



A 22-year-old stared at the sun while under the influence of lysergic acid (LSD) and suffered a blinding burn to his macula with gross permanent blinding. He remains legally blind as a result. Lasers are capable of producing similar injuries even more quickly than sunlight.

6 Retinal injury by laser



This fundus photograph of a patient's eye shows the effect of a laser on the retina (white retinal oedema) with incipient central retinal vein occlusion (note dilated tortuous veins and scattered small retinal haemorrhages). The superior lesion (large arrow) was caused by high energy argon laser directed to rupture the retinal vein and Bruch's membrane (between the retina and underlying choroid) in order to induce a chorio-retinal venous shunt. The inferior lesion (small arrow) produced a preretinal haemorrhage. Laser weapons would produce comparable lesions.

In experimental studies, it seems that the maximal temperature increases in the neuroretina are 3°C per milliwatt of laser power entering the eye.⁸ In most accidental situations, the damage caused by lasers ensues from thermomechanical mechanisms rather than from true ionisation, with generation of severe mechanical disturbances and pressure waves initiated by the rapid change of power delivered to the retina.⁹

The most significant damage is caused by rupturing Bruch's membrane between the deepest retinal layer and the underlying vessels in the choroid. The irradiance required to produce a threshold lesion is very close to that which produces a haemorrhage, and haemorrhage almost invariably accompanies an accidental exposure that gives rise to serious visual consequences. These haemorrhages may be subretinal (producing a blind spot), intraretinal (also producing a blind spot around the lesion), subhyaloid (producing a barrier to light passage), or vitreous haemorrhage. The latter can lead to vitreous breakdown and production of atypical collagen, which contracts, leading to retinal detachment and blindness (Box 6).

Ophthalmologists who frequently employ lasers to treat diabetic retinal disease tend to have blue/green colour defects caused by prolonged viewing of the reflection of the aiming beam from the patient's fundus.¹⁰

Most laser damage results in more or less focal scotomata or loss of vision. The current therapy for diabetic retinopathy is to place 2000–3000 laser burns in a scatter pattern to destroy

ischaemic retina. This results in limited field loss to the recipient. Most of these burns will cause areas of photoreceptor cell loss, but intermediary neurones will still connect viable areas of photoreceptors between the burns. In contrast, a single lesion of the fovea may result in such visual impairment that the victim can be legally registered as blind in that eye.¹¹

Almost all reported laser accidents involved damage to the macula.¹² Usually the victim is looking at a piece of optical equipment or has been attracted to some light source in the visual field. The laser pulse has then struck the retina in the central region and produced significant visual loss.

If a person receives a laser burn to the central retina he/she will be immediately aware of it and will usually present to a clinician. Routine retinal examination of people who work with lasers virtually never reveals lesions in the central retina. However, peripheral or equatorial burn will probably not be noted by the victim, as vision is usually not compromised.

Foveal burns result in the greatest loss of vision, followed by lesions in the macular region. Lesions medial to the fovea disrupt the maculopapillary bundle and result in arcuate visual field deficits. Laser injuries producing haemorrhagic lesions result in greater damage to vision because of blood spreading across the foveal region (this is worse if the lesion is sited in the upper area of the eye, as gravity causes blood to flow over the central retina). Strikes to the optic disc itself or to the nasal side of the disc rarely produce visual disturbances.

The potency of lasers has made it possible to develop laser weapons designed to blind soldiers (this would be against international law). In the next part of this report I will consider laser weapons and other uses of lasers in the military.

References

1. Boergen K, Birngruber R, Hillenkamp F. Laser-induced endovascular thrombosis as a possibility of selective vessel closure. *Ophthalmic Res* 1981; 13: 139-150.
2. Borisch W, Boergen K. Heat-induced contraction of blood vessel. *Laser Surg Med* 1982; 2: 1-13.
3. Seiler T, Marshall J, Rothery S, et al. The potential of an infrared hydrogen fluoride (HF) laser (3.0µm) for corneal surgery. *Lasers Ophthalmol* 1986; 1: 49-60.
4. Klapper R (editor). Neodymium:YAG laser microsurgery: fundamental principle and clinical applications. *Int Ophthalmol Clinics* 1985; 25(3): 1-195.
5. Plesch A, Klingbeil V, Bille J. Digital laser scanning fundus. *Applied Optics* 1987; 26: 1480.
6. Gabel VP, Birngruber R, Nasewann J. Fluorescein angiography with the scanning laser ophthalmoscope (SLO). *Laser Light Ophthalmol* 1988; 2: 35-40.
7. Boettner EA, Wolter J. Transmission of the ocular media. *Invest Ophthalmol* 1962; 1: 776-783.
8. Birngruber R, Hillenkamp F, Gabel VP. Theoretical investigation of laser thermal injury. *Health Phys* 1985; 48: 781-796.
9. Marshall J. Thermal, mechanical mechanisms and laser damage to the retina. *Invest Ophthalmol* 1970; 9: 97-115.
10. Grunduz K, Arden GB. Changes in colour contrast sensitivity associated with operating argon lasers. *Br J Ophthalmol* 1989; 73: 241-246.
11. Marshall J. Structural aspects of laser-induced damage and their functional implications. *Health Physiol* 1989; 56: 617-624.
12. Boldrey EE, Little HL, Flocks M, et al. Retinal injury due to industrial laser burns. *Ophthalmology* 1981; 88: 101-107.

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